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13. ABSTRACT *(Maximum 200 words)*
Completed work on this grant analyzes problems of 3-D vision, visual search, spatial mapping, planning and action, all of which utilize spatial representations to control adaptive behaviors in real time. Highlights include significant contributions towards solving the classical figure-ground problem for biological vision, the motor equivalence problem for flexible arm movement control including tool use, the problem of self-organizing body-centered spatial representations for movement planning and spatial orientation, and the problem of carrying out fast visual search for targets among multiple distractors. New research directions include projects which have been developed to frontally attack core problems concerning how a rapidly moving agent can self-organize spatial representations, use these representations for real-time movement planning, and transform spatial movement plans into appropriate motor commands for movement control and real-time navigation. Specific projects include retinal image processing, formation of egocentric maps of object positions from optic flow, detection of moving objects from optic flow, integration of egocentric and allocentric representations for autonomous navigation, investigation of spatial reference frames and transformations between frames for real-time flexible speech articulator control.

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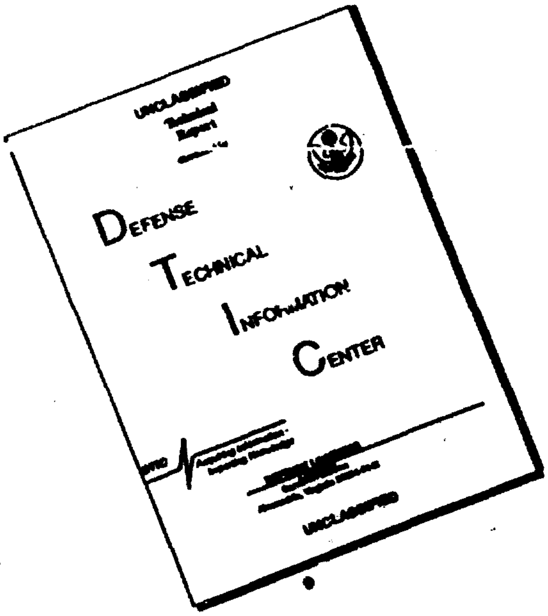

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AEOSR-TR- 94 0116

INFORMATION RELATED TO AFOSR F49620-92-J-0499
SEPTEMBER 1, 1992 - JUNE 30, 1993
CENTER FOR ADAPTIVE SYSTEMS
AND
DEPARTMENT OF COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

August 27, 1993

1 Publications

Number of peer-reviewed publications: 7

Number of book chapters: 1

Number of other articles: 6

See the attached Progress Report for details.

2 Committees

Number of committees: 44

Professor Paolo Gaudiano served as a referee for 27 papers in the session on robotics and control for the World Congress on Neural Networks (WCNN'93), Portland, Oregon, July, 1993.

Professor Gaudiano is a member of the Faculty Council at Boston University.

Professor Gaudiano is on the Natural Science Curriculum Committee at Boston University.

Professor Gaudiano served on the Boston University Alumni Award Committee as Faculty Council Representative.

Professor Gaudiano served on 8 dissertation committees; he served as first reader on 1 committee, chairman on 2 committees, and third reader on 2 committees.

Professor Stephen Grossberg organized an invited symposium on neural networks held during the annual meeting of the Society for Industrial and Applied Mathematics in Snowbird, Utah in October, 1992.

Professor Grossberg organized an invited symposium on learning and memory held at the AAAS annual meeting in Boston in February, 1993.

Professor Grossberg was Program Chairman for the 1993 World Congress on Neural Networks (WCNN'93), Portland, Oregon, July, 1993.

Professor Grossberg was on the Program Committee for the International Conference on Artificial Neural Networks (ICANN'93) to be held in Amsterdam, The Netherlands in September, 1993.

Professor Grossberg is on the Program Committee for the International Joint Conference on Neural Networks (IJCNN'93) to be held in Nagoya, Japan in October, 1993.

Professor Grossberg is on the Program Committee for the 5th International Conference on Information Processing and Management of Uncertainty in Knowledge-Based Systems (IPMU) to be held in Paris, France.

Professor Grossberg is on the Advisory and Program Committees for the 5th UNB Artificial Intelligence Symposium to be held in Fredericton, New Brunswick, Canada.

Professor Grossberg served on the Program Committee for the Second International Conference on Fuzzy Logic and Neural Networks, Iizuka, Japan.

Professor Grossberg was re-elected to the Governing Board of the International Neural Network Society for another three-year term.

Professor Grossberg was appointed to the editorial board of the journal *IEEE Transactions on Neural Networks.*

Professor Grossberg was appointed to the editorial board of the *International Journal of Uncertainty, Fuzziness, and Knowledge-Based Reasoning.*

Professor Grossberg served on 11 dissertation committees; he served as first reader on 4 committees, second reader on 5 committees, and third reader on 1 committee.

Professor Grossberg is chairman of the Boston University Neuroscience Search Committee which is charged with hiring a Director for a new Center for Neuroscience.

Professor Frank Guenther served on 9 dissertation committees; he served as chairman on 2 committees and third reader on 2 committees.

3 Transition Stories

From June 4 to July 9, 1993, Professor Paolo Gaudiano worked with a group headed by Juan López Coronado at the University of Valladolid, Spain to develop a system for real-time adaptive control of a mobile robot, including the ability to use intermittent or continuous visual feedback and to automatically recalibrate its spatial trajectory in response to changes in system parameters. This work is being prepared for publication, and plans are in place to implement this in an actual mobile robot. This group also plans future work on goal-directed reaching using the DIRECT model, whose development was partially supported by the current grant. This work involves motor equivalent reaching by a multijoint robotic arm, embodying a solution to the classical motor equivalence problem; that is, the system can perform reaches to a target using different joint movements to compensate for different environmental constraints. Such compensation occurs automatically, i.e. without

requiring new learning to handle unexpected constraints. The DIRECT model provides the theoretical basis for performance of reaches using tools and reaches with blocked joints, thus making it ideal for a robust, flexible robotic arm controller.

Related work in robotics is also being done at MIT Lincoln Laboratories and Symbus Technology. At Lincoln laboratories, an autonomous mobile robot named MAVIN has been implemented using reinforcement learning networks developed by Professor Grossberg. At Symbus, Michael Kuperstein has implemented a robotic arm whose theoretical basis includes work done in collaboration with Professor Grossberg on hand-eye coordination and motor performance.

Conference and colloquium presentations have provided further contact with industry and other research institutions. The following oral presentations have been given:

1. Gaudiano, P., Oral presentation at the 15th European Conference on Visual Perception, entitled "Mulitplicative and subtractive adaptation in a push-pull model of spatiotemporal retinal processing," Pisa, Italy, September, 1992.

2. Gaudiano, P., Invited symposium talk at the Meeting on Judgment and Decision Making, entitled "Neural dynamics of decision making under risk," St. Louis, Missouri, November, 1992.

3. Gaudiano, P., Invited talk at the SPIE conference Sensor Fusion V, entitled "Linear responses to nonlinear signals: A neural network model of spatiotemporal visual processing," Boston, November, 1992.

4. Gaudiano, P., Invited colloquium, entitled "How does the retina work? A neural network model of the vertebrate retina applied to physiological and psychophysical data," Northeastern University, Department of Psychology, Boston, November, 1992.

5. Gaudiano, P., Guest lecture in CN730, entitled "Modeling retinal ganglion cells with shunting networks," Boston University, January, 1993.

6. Gaudiano, P., Invited presentation at ARVO's Nonlinear Systems Analysis Special Interest group meeting, entitled "A nonlinear push-pull model of retinal processing," Sarasota, Florida, May, 1993.

7. Gaudiano, P., Invited colloquium at the Universidad de Valladolid, Spain, entitled "Vector associative maps: Real-time, error-based learning and control of movement trajectories," June, 1993.

8. Gaudiano, P., Invited colloquium at the Universidad de Valladolid, Spain, entitled "A nonlinear model of spatiotemporal retinal image processing," June, 1993.

9. Gaudiano, P., Invited colloquium at the University of Madrid, Spain, June, 1993.

10. Gaudiano, P., Poster and invited oral presentation at the AAAS Science Innovation Conference entitled: "An unsupervised error-based neural network model for the generation and control of movement trajectories", Boston, Massachusetts, August, 1993.

11. Grossberg, S., Invited lecture, meeting on Dynamics, Competition, and Neural Networks, Boston University, July, 1992.

12. Grossberg, S., Invited lecture, Brain and Mind Conference, Royal Danish Academy of Science and Letters, Copenhagen, Denmark, August, 1992.

13. Grossberg, S., Invited lecture, International Conference on Artificial Neural Networks, Brighton, England, September, 1992.

14. Grossberg, S., Colloquium, Department of Psychology, Harvard University, September, 1992.

15. Grossberg, S., Colloquium, Department of Cognitive and Neural Systems, Boston University, September, 1992.

16. Grossberg, S., Invited lecture, IEEE Neural Networks Pioneer Award, October, 1992.

17. Grossberg, S., Colloquium, Cognitive Science Department, Princeton University, October, 1992.

18. Grossberg, S., Invited lecture, annual meeting of the Memory Disorders Society, Boston, October, 1992.

19. Grossberg, S., Lecture at the annual meeting of the Society for Neuroscience, Anaheim, California, October, 1992.

20. Grossberg, S., Invited lecture, International Conference on Dynamical Systems, Society for Industrial and Applied Mathematics, Snowbird, Utah, October, 1992.

21. Grossberg, S., Invited lecture, International Conference on Neuroimaging, Boston, November, 1992.

22. Grossberg, S., Invited lecture, annual meeting of the American Association for the Advancement of Science, Boston, February, 1993.

23. Grossberg, S., annual Linnaeus Lecture, Uppsala University, Sweden, February, 1993.

24. Grossberg, S., Invited lecture, Department of Computer Systems, Uppsala University, Sweden, February, 1993.

25. Grossberg, S., Invited lecture, Workshop on Neural Networks, Uppsala University, Sweden, February, 1993.

26. Grossberg, S., Colloquium, Department of Psychology, Johns Hopkins University, Baltimore, Maryland, March, 1993.

27. Grossberg, S., Colloquium, Department of Neuroscience, Brown University, Providence, Rhode Island, March, 1993.

28. Grossberg, S., Invited lecture, meeting on Neural Representation of Temporal Patterns, Duke University, April, 1993.

29. Grossberg, S., Invited lecture, international conference on the Neural Control of Movement, Marco Island, Florida, April, 1993.

30. Grossberg, S., Lecture, annual meeting of the Association for Research in Vision and Ophthalmology (ARVO), Sarasota, Florida, May, 1993.

31. Grossberg, S., Three poster presentations, annual meeting of the Association for Research in Vision and Ophthalmology (ARVO), Sarasota, Florida, May, 1993.

32. Grossberg, S., Invited lecture, International NATO conference: "From Statistics to Neural Networks," Les Arcs, France, June, 1993.

33. Grossberg, S., Plenary lecture at the World Congress on Neural Networks entitled "3-D vision and figure-ground pop-out", Portland, Oregon, July, 1993.

34. Grossberg, S., Invited lecture at the World Congress on Neural Networks entitled "Learning, recognition, reinforcement, attention, and timing in a thalamo-cortico-hippocampal model", Portland, Oregon, July, 1993.

35. Guenther, F. H., oral presentation at the World Congress on Neural Networks entitled "A self-organizing neural model for motor equivalent phoneme production", Portland, Oregon, July, 1993.

36. Guenther, F. H., oral presentation at the World Congress on Neural Networks entitled "A self-organizing neural network for learning a body-centered invariant representation of 3-D target position", Portland, Oregon, July, 1993.

4 Other Funding Sources

The following source has also funded work partially supported by the AFOSR grant.

1. Sloan Foundation, "Sloan Research Fellowship;" June 1, 1992–September 15, 1994; $30,000 (2-year total); Professor Paolo Gaudiano, PI.

The following grants partially support Professor Grossberg, who works on the AFOSR grant on a cost-sharing basis paid indirectly by his endowed chair.

1. ARPA, "Self-organizing neural network architectures for incremental learning, pattern recognition, and image understanding;" June 1, 1992–May 31, 1995; $732,753 (3-year total); Professor Gail Carpenter and Professor Stephen Grossberg, co-PI's.

2. National Science Foundation, "Adaptive sensory-motor planning by humans and machines" (year 2 of 2); July 1, 1991–December 31, 1993; $323,380 ($163,380 second year); Professor Stephen Grossberg and Professor Daniel Bullock, co-PIs.

3. Office of Naval Research, "Real-time neural models of 3-D vision and object recognition;" (year 2 of 3); September 30, 1991–September 29, 1994; $621,530 ($207,053 second year); Professor Gail Carpenter and Professor Stephen Grossberg, co-PIs.

4. Office of Naval Research, "Self-organizing neural circuits for sensory-guided motor control" (years 1 and 2 of 3); February 1, 1992–January 31, 1995; $350,266 ($227,768 first and second years); Professor Daniel Bullock and Professor Stephen Grossberg, co-PIs.

5 Additional Information

Included is a progress report submitted to you earlier this year (July 28) that describes in more detail the work we have done. This report lists completed articles, selected abstracts from these articles, and projects in progress.

AFOSR

Boston University

College of Liberal Arts
111 Cummington Street, Second Floor
Boston, Massachusetts 02215

Center for Adaptive Systems
617/353-7857, 7858

July 28, 1993

Lt. Colonel Dan Collins
Air Force Office of Scientific Research
Building 410
Bolling AFB, DC 20332-6448

Re: AFOSR F49620-92-J-0499

Dear Lt. Colonel Collins,

I have enclosed some information about progress on our grant entitled **Neural Models of Spatial Orientation in Novel Environments** for which work began on September 1, 1992. The summary lists completed articles, selected abstracts of these articles, and work in progress.

Completed work analyses problems of 3-D vision, visual search, spatial mapping, planning and action, all of which utilize spatial representations to control adaptive behaviors in real time. Highlights include significant contributions towards solving the classical figure-ground problem for biological vision; the motor equivalence problem for flexible arm movement control, including tool use; the problem of self-organizing body-centered spatial representations; for spatial orientation; and the problem of carrying out fast visual search for targets among multiple distractors. The section on New Directions outlines projects which have been developed to frontally attack core problems concerning how a rapidly moving agent can self-organize spatial representations for navigating a complex environment in real time.

Please let me know if you need more information.

We are looking forward to your visit.

Best wishes,

Steve Grossberg

Stephen Grossberg
Wang Professor of Cognitive and Neural Systems
Professor of Mathematics, Psychology, and
Biomedical Engineering
Director, Center for Adaptive Systems
Chairman, Department of Cognitive
and Neural Systems

Enclosures:

1) j. cog. neurosci. 1993
2) biol. cyb. 1993
3) P & P 1993
4) grossberg, mingolla, ross
5) neural reps III preprint

PUBLICATIONS PARTIALLY SUPPORTED BY
THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

CONTRACT AFOSR F49620-92-J-0499

SEPTEMBER 1, 1992—JUNE 30, 1993

CENTER FOR ADAPTIVE SYSTEMS
AND
DEPARTMENT OF COGNITIVE AND NEURAL SYSTEMS
BOSTON UNIVERSITY

1. Bullock, D., Contreras-Vidal, J.L. and Grossberg, S. (1993). Cerebellar learning in an opponent motor controller for adaptive load compensation and synergy formation. **Technical Report CAS/CNS-TR-93-009**, Boston University. In **Proceedings of the world congress on neural networks**, Portland. Hillsdale, NJ: Erlbaum Associates. (*@)
2. Bullock, D., Greve, D., Grossberg, S., and Guenther, F.H. (1993). A self-organizing neural network for learning a body-centered invariant representation of 3-D target position. **Technical Report CAS/CNS-TR-93-010**, Boston University. In **Proceedings of the world congress on neural networks**, Portland. Hillsdale, NJ: Erlbaum Associates. (+)
3. Bullock, D., Grossberg, S., and Guenther, F.H. (1993). A self-organizing neural model of motor equivalent reaching and tool use by a multijoint arm. *Journal of Cognitive Neuroscience*, in press. (+@)
4. Bullock, D., Grossberg, S., and Mannes, C. (1993). A neural network model for cursive script production. *Biological Cybernetics*, in press. (*+@)
5. Carpenter, G.A., Grossberg, S., and Lesher, G. (1993). The what-and-where filter: A spatial mapping neural network for object recognition and image understanding. **Technical Report CAS/CNS-TR-93-043**, Boston University. In preparation. (*#+@)
6. Fischl, B., Gaudiano, P., Olson, S., and Tal, D. (1993). A neural network model of dynamic receptive field reorganization. *Society for Neuroscience Abstracts*, in press.
7. Gaudiano, P. (1993). A nonlinear model of spatiotemporal retinal processing: Simulations of X and Y retinal ganglion cell behavior. **Technical Report CAS/CNS-TR-93-048**, Boston University. Submitted for publication to *Vision Research*.
8. Gaudiano, P. (1993). An unsupervised error-based neural network model for the generation and control of movement trajectories. In **Proceedings of the AAAS Science Innovation Conference**, in press.
9. Gaudiano, P. (1993). Motivation. In M.A. Arbib (Ed.), **The handbook of brain theory and neural networks**. Cambridge, MA: MIT Press, in preparation.
10. Grossberg, S. (1993). Boundary, brightness, and depth interactions during preattentive representation and attentive recognition of figure and ground. **Technical Report CAS/CNS-TR-93-003**, Boston University. Invited chapter in celebration of the 80th birthday of Professor Gaetano Kanizsa and the 20th anniversary of the Italian Journal of Psychology. (*@)

11. Grossberg, S. (1993). 3-D vision and figure-ground separation by visual cortex. **Technical Report CAS/CNS-TR-92-019**, Boston University. *Perception and Psychophysics*, in press. (*@)

12. Grossberg, S., Mingolla, E., and Ross, W.D. (1993). A neural theory of attentive visual search: Interactions of visual, spatial, and object representations. **Technical Report CAS/CNS-TR-93-038**, Boston University. Submitted for publication to *Psychological Review*. (*+@)

13. Guenther, F.H. (1993). A self-organizing neural model for motor equivalent phoneme production. **Technical Report CAS/CNS-TR-93-025**, Boston University. In **Proceedings of the world congress on neural networks**, Portland. Hillsdale, NJ: Erlbaum Associates, in press.

14. Guenther, F.H. (1993). Sensorimotor transformations in a neural model of motor equivalent speaking. *Society for Neuroscience Abstracts*, in press.

15. Guenther, F.H., Bullock, D., Greve, D., and Grossberg, S. (1993). Neural representations for sensory-motor control, III: Learning a body-centered representation of 3-D target position. **Technical Report CAS/CNS-93-045**, Boston University. Submitted for publication to *Journal of Cognitive Neuroscience*. (+@)

16. Zalama Casanova, E., Gaudiano, P., and Lopéz Coronado, J. (1993). A real-time, unsupervised neural network model for the control of a mobile robot in nonstationary environments. In preparation.

* Also supported in part by ARPA.

Also supported in part by British Petroleum.

+ Also supported in part by the National Science Foundation.

@ Also supported in part by the Office of Naval Research.

SOME NEW DIRECTIONS OF RESEARCH IN PROGRESS

Contract AFOSR F49620-92-J-0499

July 26, 1993

1. Building an Egocentric Map of Object Positions using Optic Flow

This work investigates the use of optic flow information to form a map representation, rather than vector representation (c.f. Guenther *et al.*, 1993), of egocentric object positions. A map representation has the advantage of allowing the positions of many objects to be represented simultaneously. Research has determined that such a representation can readily be formed from the flow field, and that this representation relates closely to the vector representations of Guenther *et al.* (1993): position on the map corresponds to the azimuth and elevation coordinates of the vector representations, and activity level at a map position can code distance from the head (the third coordinate in the vector representation).

This work is in progress, with further research needed to integrate this representation with the Boundary Contour System (e.g., Grossberg, 1993) and to apply this representation to the problem of navigation.

2.Detecting Moving Objects from Optic Flow

This project investigates the problem of directing attention to a moving object in the field of vision when the observer himself is moving (e.g., a running animal that must attend to a moving object in the periphery which may be an approaching predator). To this end, a computer display that produces flow fields and allows manipulation of parameters such as the size and density of objects, as well as the speed and acceleration of moving objects, has been created. This display is being used to investigate stimulus types that are readily segmented from the rest of the flow field.

This project is in the early stages.

3. Integrating Egocentric and Allocentric Representations for Navigation

This project investigates the use of egocentric representations of landmark locations in combination with stored allocentric representations of goal locations (such as the location of buried food or other hidden targets) to form movement paths from the current location to the remembered goal. Research has shown that a polar egocentric representation, consisting of the distance and azimuth components of the vector representations described in Guenther *et al.* (1993), is ideal for this task This is because an egocentric polar representation can be transformed into allocentric coordinates simply by adding an offset corresponding to allocentric direction (similar to a compass reading).

This work is in progress, with further research needed to incorporate map representations of egocentric space and to deal with obstacle locations in path planning.

4. Autonomous Navigation in a Novel Environment

Perceiving the location and motion of objects in the environment is necessary but not sufficient for survival. At each moment in time the organism must decide what actions to

take by combining sensory information and prior learning. These decisions may involve for instance the selection of only one out of many objects to which the organism must attend.

As a first approach to this problem, in collaboration with graduate students, we have abstracted the general idea of animal navigation through a nonstationary environment, into the simpler problem of an organism or machine moving over flat terrain that includes threats, temporary goals, and an ultimate goal. This abstraction allows us to make a number of initial simplifying assumptions, which can be relaxed in later phases of project development.

Our goal is the following: given a set of goals and/or threats, with one ultimate goal representing the organism's final destination, how can we generate a meaningful time-varying spatial target that can be used to guide the organism around obstacles, over temporary goals, and to its final destination? The solution we have begun to investigate is based on Grossberg's *conditioning circuit* (Grossberg, 1971, 1982), which has already been successfully applied to several problems including classical and operant conditioning (Grossberg, 1982; Grossberg and Levine, 1987; Grossberg and Schmajuk, 1987), and decision making under risk (Grossberg and Gutowski, 1987).

Our application of the conditioning circuit to goal-oriented navigation is inspired by Grossberg's suggestion (Grossberg, 1982, pp. 64–67) that the output of the decision-making circuit could be subdivided into at least two separate pathways: one excitatory pathway modulates attentional feedback, leading to enhanced activation of those sensory cues that are selected for processing; another pathway carries motor incentive, which can have positive or negative affective value, depending on whether the selected cue is interpreted as a goal or threat. The motor incentive outputs control approach-avoidance behavior by differentially gating the activation of each (active) sensory representation on its way to a pair of maps, one representing the organism's approach tendency, and the other representing the organism's avoidance tendencies.

We suggest in a similar fashion that each object activates not only a sensory representation that is used in the conditioning circuit, but also a pair of nodes that represent the (x, y) coordinates of the object's spatial location (or alternatively the distance and angle to the object), which is presumed to be known on the basis of visual information or spatial memory. The output of the decision-making circuit, in addition to focusing attention on relevant objects, determines whether the spatial coordinates of the relevant objects are mapped to the approach or avoidance spatial maps, as shown in Figure 1.

As an initial step in determining the nature of the approach-avoidance interactions, we are analyzing the case wherein the conditioning circuit chooses a single goal and a single threat. The idea is the following: if the activation that appears on the goal and threat maps is in the form of a Gaussian whose peak is determined by the (x, y) coordinates of the selected goal and threat, how can we use available information to modulate the size (amplitude or standard deviation) of each Gaussian as a function of its position relative to the organism, so as to obtain a time-varying shifting peak that guides the organism to the goal, avoiding the threat(s)? The idea combines the simple *peak shift* property of Gaussians, with some of the motor-to spatial maps (e.g., Gaudiano and Grossberg, 1991; Grossberg and Kuperstein, 1989). "Peak shift" refers to the observation that when a positive Gaussian is added to a negative Gaussian centered at a different location, the resulting function has a positive peak whose location relative to the peak of the original positive Gaussian is displaced away from the location of the peak of the negative Gaussian. Hence it is possible to represent goals and

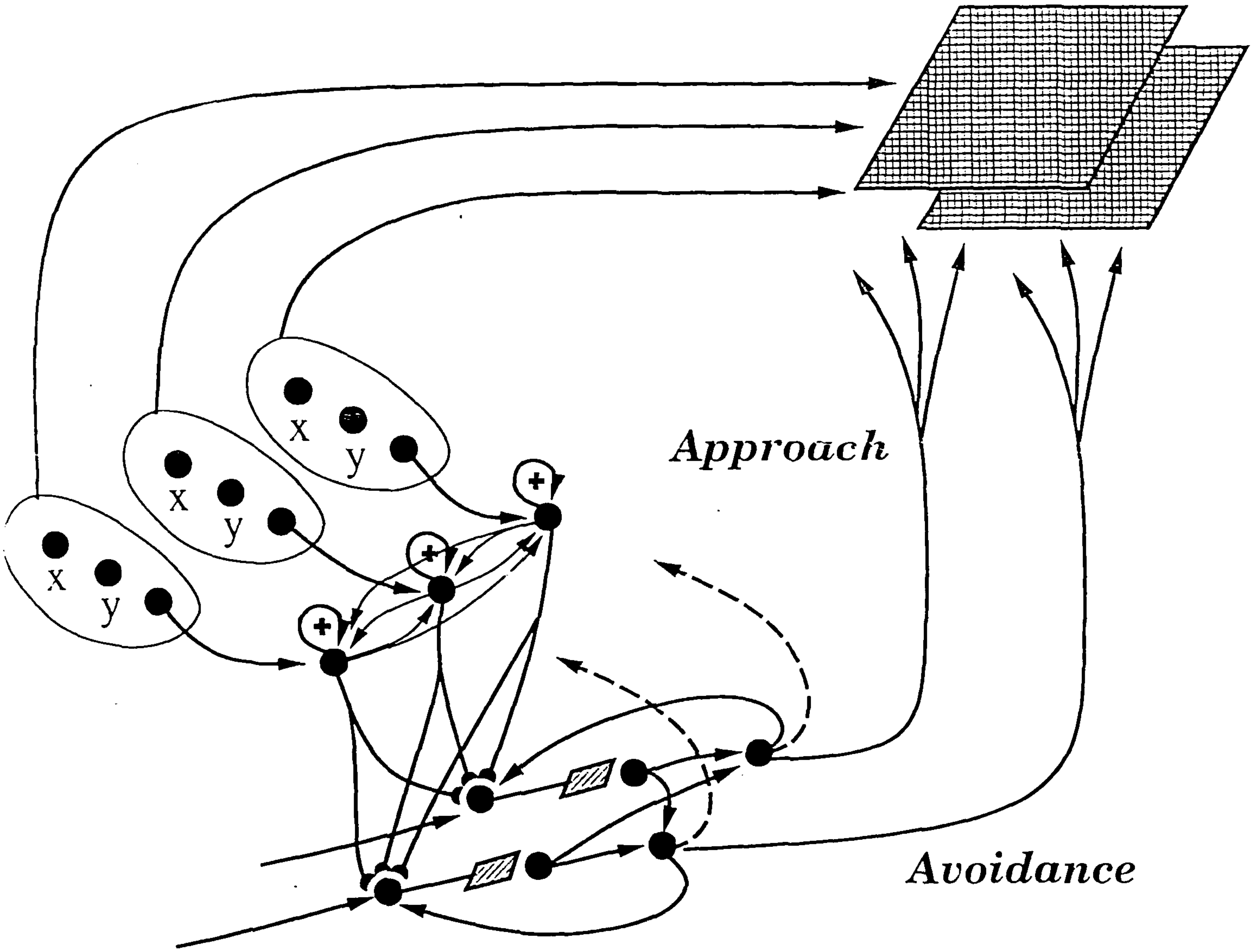

Figure 1. Schematic diagram illustrating how sensory-drive heterarchy activation can gate positional information of each object either to the goal (approach) map, or to the threat (avoidance) map. Only two of many channels are shown in the sensory-drive heterarchy.

threats, respectively, as positive and negative Gaussians that are combined in one spatial map. As result of the peak shift property, the point of maximum activation will be shifted away from the actual goal to avoid threats. A recurrent competitive field can select the peak of activation at each time step, thus providing an instantaneous goal direction, which can be used as input to a motor control module, causing the organism to follow a curved trajectory around threats on the way to a goal.

Obviously this initial approach is limited in what it can handle. The most important criticisms are (1) can the simple Gaussians lead to satisfactory results even in the single-goal, single-threat case? and (2) how can we take into account more global path planning of the kind exhibited even in simple animals? As far as point (1) is concerned, the preliminary results (and prior experience with Gaussian peak shifts) suggests that we can get reasonable results. Regarding point (2), we think that the conditioning circuit can be crucial in providing meaningful goals (threats) or sets of goals (threats). Investigation along these lines is expected to continue in the future.

5. The Control of a Mobile Robot

The final element of this project deals with the control of a mobile robot. This part of the work serves three purposes: first, it shows how the kind of information generated by the approach-avoidance maps can be used to generate valid movement commands in an unstationary or novel environment. Secondly, this work extends our prior models for the control of arm movement trajectories (Bullock, Grossberg, and Guenther, 1992; Gaudiano and Grossberg, 1991) to the problem of unrestricted movements in the environment. Third, this work represents a practical application and shows its usefulness in the fields of robotics and control.

The proposed model (illustrated in Figure 2) uses a combination of the VAM and DIRECT models for the control of an unsupervised, real-time, autonomous mobile robot in a nonstationary environment. In collaboration with researchers at the Department of Systems and Automation Engineering of the University of Valladolid (Spain), I have developed a model for the adaptive control of a mobile robot that can navigate in a 2-D environment. We are currently preparing an article that we plan to submit to *Neural Networks*. The model combines associative learning and VAM learning to generate transformations between spatial and velocity coordinates. The transformations are generated in an initial training phase, during which the robot moves as a result of endogenously generated velocities applied to the robot's wheels. The robot learns the relationship between these small velocities and the resulting incremental movements. During performance, the use of a VAM architecture enables the robot to generalize from the learned incremental movements to reach targets at arbitrary distance and angle from the robot. The VAM structure also enables the robot to perform successfully in spite of drastic changes to the robot's plant, including changes in wheel radius, changes in inter-wheel distance, or changes in the internal time step of the system.

The on-line nature of VAM learning enables the robot to adapt over time to these changes. An additional VAM module is used to learn the inverse transformation, between angular velocities and the resulting displacements. This inverse transformation, which was inspired by the inverse transformation found in the DIRECT model, can supplement or supplant visual information, a competence that is very useful if the robot's visual system is

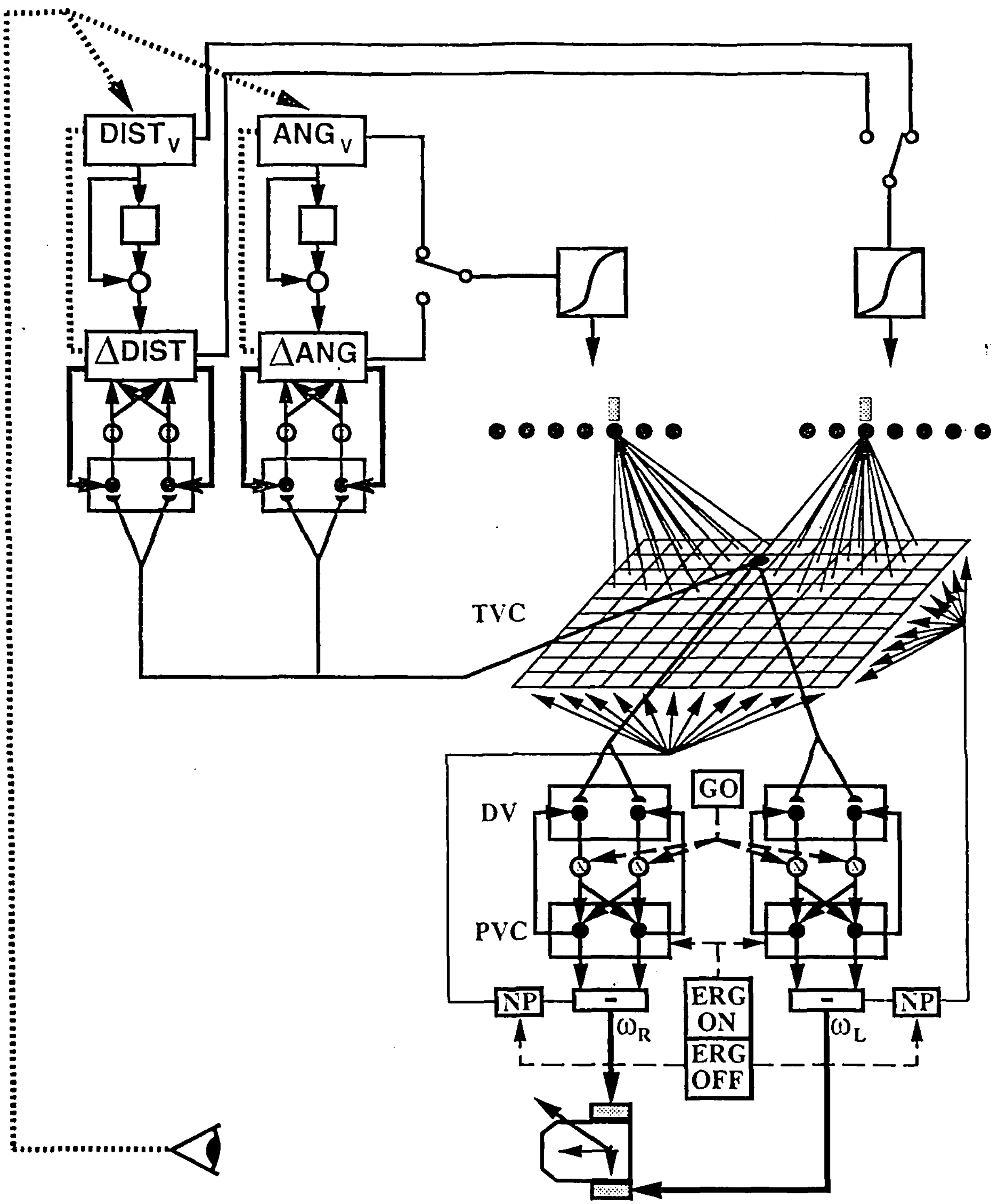

Figure 2. Proposed neural network model for the control of a mobile robot. The populations on the right of the figure learn to transform distance and angle commands into correct angular velocities to move the robot towards an arbitrary target. The populations on the left allow the robot to learn an inverse transformation, which determines how the distance and angle to a given target changes as a result of a given pair of wheel velocity commands. The inverse mapping can be used to complement or supplant visual information.

slow or inaccurate (as is typically the case in practical applications). Thus far our efforts have concentrated on developing the model and doing computer simulations. Once this article is completed we will transfer this onto the real robot. In addition to the article for *Neural Networks*, we are planning to prepare another article that deals more extensively with the robotics and control aspect of this project, for submission to a different journal.

6. A Neural Network Model of Speech Acquisition and Motor Equivalent Speech Production

This research investigates the problem of how infants learn to produce the speech sounds of their native language in a way that affords motor equivalence. A babbling cycle is used to self-organize two mappings: one between an acoustic space and an orosensory space, and one between orosensory space an articulator movements. Targets in orosensory space are specified as convex hull attractors, rather than the traditional point attractor targets. In a manner analogous to the DIRECT model of reaching (Bullock, Grossberg, and Guenther, 1993), desired movement *directions* in orosensory space are then mapped into *velocities* in articulator space to provide motor equivalence. This work thus gives further insight into appropriate forms of spatial representation for movement planning. Simulations verify the model's ability to self-organize and to automatically (i.e., without practice or new learning) compensate for perturbations to the articulators.

A journal article is in preparation.

7. Speech Acquisition, Coarticulation, and Speaking Rate Effects in a Neural Network Model

This work investigates the relationship of a convex hull theory of speech production to data on coarticulation and speaking rate effects. Convex hull targets allow a natural explanation of coarticulation: if the target of a future phoneme overlaps the target of the current phoneme along an orosensory dimension, then movements can begin toward the region of overlap. Speaking rate effects as seen in human subjects arise from an application of Fitt's Law to the convex hull theory: increased speaking rate is carried out by both increasing movement "effort" *and* increasing the size of the convex hull target. This can explain the heretofor anomolous experimental result of increased speed of movement for consonants but *decreased* speed of movement for vowels when the speaking rate is increased. Simulation results have verified these ideas.

This work is to be presented at the Society for Neuroscience annual meeting in November, 1993, and a journal article is in preparation.

References

Bullock, D., Grossberg, S., and Guenther, F. (1992). A self-organizing neural network model for redundant sensory-motor control, motor equivalence, and tool use. **Technical Report CAS/CNS-TR-92-004**, Boston University.

Gaudiano, P. and Grossberg, S. (1991). Vector associative maps: Unsupervised real-time error-based learning and control of movement trajectories. *Neural Networks*, **4**, 147–183.

Grossberg, S. (1971). On the dynamics of operant conditioning. *Journal of Theoretical Biology*, **33**, 225–255.

Grossberg, S. (1982). A psychophysiological theory of reinforcement, drive, motivation and attention. *Journal of Theoretical Neurobiology*, **1**, 286–369.

Grossberg, S. and Gutowski, W. (1987). Neural dynamics of decision making under risk: Affective balance and cognitive-emotional interactions. *Psychological Review*, **94**, 300–318.

Grossberg, S. and Kuperstein, M. (1989). **Neural dynamics of adaptive sensory-motor control: Expanded edition**. Elmsford, NY: Pergamon Press.

Grossberg, S. and Levine, D. (1987). Neural dynamics of attentionally modulated Pavlovian conditioning: blocking, interstimulus interval, and secondary reinforcement. *Applied Optics*, **26**, 5015–5030.

Grossberg, S. and Schmajuk, N.A. (1987). A neural network architecture for attentionally-modulated Pavlovian conditioning: Conditioned reinforcement, inhibition, and opponent processing. *Psychobiology*, **15**, 195–240.

Guenther, F.H. (1993). A self-organizing neural model for motor equivalent phoneme production. **Technical Report CAS/CNS-TR-93-025**, Boston University. In **Proceedings of the world congress on neural networks**, Portland. Hillsdale, NJ: Erlbaum Associates.

Guenther, F.H. (1993) Sensorimotor transformations in a neural model of motor equivalent speaking. *Societ for Neuroscience Abstracts*, November 1993, in press.

3-D VISION AND FIGURE-GROUND SEPARATION BY VISUAL CORTEX

Stephen Grossberg†

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Boston, MA: Boston University

Perception and Psychophysics, in press, 1993

ABSTRACT

A neural network theory of 3-D vision, called FACADE Theory, is described. The theory proposes a solution of the classical figure-ground problem for biological vision. It does so by suggesting how boundary representations and surface representations are formed within a Boundary Contour System (BCS) and a Feature Contour System (FCS). The BCS and FCS interact reciprocally to form 3-D boundary and surface representations that are mutually consistent. Their interactions generate 3-D percepts wherein occluding and occluded object parts are separated, completed, and grouped. The theory clarifies how preattentive processes of 3-D perception and figure-ground separation interact reciprocally with attentive processes of spatial localization, object recognition, and visual search. A new theory of stereopsis is proposed that predicts how cells sensitive to multiple spatial frequencies, disparities, and orientations are combined by context-sensitive filtering, competition, and cooperation to form coherent BCS boundary segmentations. Several factors contribute to figure-ground pop-out, including: boundary contrast between spatially contiguous boundaries, whether due to scenic differences in luminance, color, spatial frequency, or disparity; partially ordered interactions from larger spatial scales and disparities to smaller scales and disparities; and surface filling-in restricted to regions surrounded by a connected boundary. Phenomena such as 3-D pop-out from a 2-D picture, DaVinci stereopsis, 3-D neon color spreading, completion of partially occluded objects, and figure-ground reversals are analysed. The BCS and FCS subsystems model aspects of how the two parvocellular cortical processing streams that join the Lateral Geniculate Nucleus to prestriate cortical area V4 interact to generate a multiplexed representation of Form-And-Color-And-DEpth, or FACADE, within area V4. Area V4 is suggested to support figure-ground separation and to interact with cortical mechanisms of spatial attention, attentive object learning, and visual search. Adaptive Resonance Theory (ART) mechanisms model aspects of how prestriate visual cortex interacts reciprocally with a visual object recognition system in inferotemporal cortex (IT) for purposes of attentive object learning and categorization. Object attention mechanisms of the What cortical processing stream through IT cortex are distinguished from spatial attention mechanisms of the Where cortical processing stream through parietal cortex. Parvocellular BCS and FCS signals interact with the model What steam. Parvocellular FCS and magnocellular Motion BCS signals interact with the model Where stream. Reciprocal interactions between these visual, What, and Where mechanisms are used to discuss data about visual search and saccadic eye movements, including fast search of conjunctive targets, search of 3-D surfaces, selective search of like-colored targets, attentive tracking of multi-element groupings, and recursive search of simultaneously presented targets.

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A NEURAL THEORY OF ATTENTIVE VISUAL SEARCH: INTERACTIONS OF VISUAL, SPATIAL, AND OBJECT REPRESENTATIONS

Stephen Grossberg†, Ennio Mingolla‡ and William D. Ross§

Technical Report CAS/CNS-TR-93-038
Boston, MA: Boston University

ABSTRACT

Visual search data are given a unified quantitative explanation by a model of how spatial maps in the parietal cortex and object recognition categories in the inferotemporal cortex deploy attentional resources as they reciprocally interact with visual representations in the prestriate cortex. The model visual representations are organized into multiple boundary and surface representations. Visual search in the model is initiated by organizing multiple items that lie within a given boundary or surface representation into a candidate search grouping. These items are matched with object recognition categories to test for matches or mismatches. Mismatches can trigger deeper searches and recursive selection of new groupings until a target object is identified. This search model is algorithmically specified to quantitatively simulate search data using a single set of parameters, as well as to qualitatively explain a still larger data base, including data of Aks and Enns (1992), Bravo and Blake (1990), Egeth, Virzi, and Garbart (1984), Cohen and Ivry (1991), Enns and Rensink (1990), He and Nakayama (1992), Humphreys, Quinlan, and Riddoch (1989), Mordkoff, Yantis, and Egeth (1990), Nakayama and Silverman (1986), Treisman and Gelade (1980), Treisman and Sato (1990), Wolfe, Cave, and Franzel (1989), and Wolfe and Friedman-Hill (1992). The model hereby provides an alternative to recent variations on the Feature Integration and Guided Search models, and grounds the analysis of visual search in neural models of preattentive vision, attentive object learning and categorization, and attentive spatial localization and orientation.

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A SELF-ORGANIZING NEURAL MODEL OF MOTOR EQUIVALENT REACHING AND TOOL USE BY A MULTIJOINT ARM

Daniel Bullock†, Stephen Grossberg†, and Frank H. Guenther‡

Journal of Cognitive Neuroscience, in press, 1993

ABSTRACT

This paper describes a self-organizing neural model for eye-hand coordination. Called the DIRECT model, it embodies a solution of the classical motor equivalence problem. Motor equivalence computations allow humans and other animals to flexibly employ an arm with more degrees of freedom than the space in which it moves to carry out spatially defined tasks under conditions that may require novel joint configurations. During a motor babbling phase, the model endogenously generates movement commands that activate the correlated visual, spatial, and motor information that are used to learn its internal coordinate transformations. After learning occurs, the model is capable of controlling reaching movements of the arm to prescribed spatial targets using many different combinations of joints. When allowed visual feedback, the model can automatically perform, without additional learning, reaches with tools of variable lengths, with clamped joints, with distortions of visual input by a prism, and with unexpected perturbations. These compensatory computations occur within a single accurate reaching movement. No corrective movements are needed. Blind reaches using internal feedback have also been simulated. The model achieves its competence by transforming visual information about target position and end effector position in 3-D space into a body-centered spatial representation of the direction in 3-D space that the end effector must move to contact the target. The spatial direction vector is adaptively transformed into a motor direction vector, which represents the joint rotations that move the end effector in the desired spatial direction from the present arm configuration. Properties of the model are compared with psychophysical data on human reaching movements, neurophysiological data on the tuning curves of neurons in the monkey motor cortex, and alternative models of movement control.

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THE WHAT-AND-WHERE FILTER: A SPATIAL MAPPING NEURAL NETWORK FOR OBJECT RECOGNITION AND IMAGE UNDERSTANDING

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Technical Report CAS/CNS-TR-93-043
Boston, MA: Boston University

In preparation, 1993

ABSTRACT

The What-and-Where filter forms part of a neural network architecture for spatial mapping, object recognition, and image understanding. The Where filter responds to an image figure that has been separated from its background. It generates a spatial map whose cell activations simultaneously represent the position, orientation, and size of the figure (where it is). This spatial map may be used to direct spatially localized attention to these image features. A multiscale array of oriented detectors, followed by competitive interactions between position, orientation, and size scales, is used to define the Where filter. The Where filter may be used to transform the image figure into an invariant representation that is insensitive to the figure's original position, orientation, and size. This invariant figural representation forms part of a system devoted to attentive object learning and recognition (what it is). The Where spatial map of all the figures in an image, taken together with the invariant recognition categories that identify these figures, can be used to learn multidimensional representations of objects and their spatial relationships for purposes of image understanding. The What-and-Where filter is inspired by neurobiological data showing that a Where processing stream in the cerebral cortex is used for attentive spatial localization and orientation, whereas a What processing stream is used for attentive object learning and recognition.

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NEURAL REPRESENTATIONS FOR SENSORY-MOTOR CONTROL, III: LEARNING A BODY-CENTERED REPRESENTATION OF 3-D TARGET POSITION

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Technical Report CAS/CNS-TR-93-045
Boston, MA: Boston University

ABSTRACT

A neural network is described to model how the brain may autonomously learn a body-centered representation of 3-D target position by combining information about retinal target position, eye position, and head position in real time. Such a body-centered spatial representation enables accurate movement commands to the limbs to be generated despite changes in the spatial relationships between the eyes, head, body, and limbs through time. The representation is a vector representation—otherwise known as a parcellated distributed representation—of target vergence with respect to the two eyes, and of the horizontal and vertical spherical angles of the target with respect to a cyclopean egocenter. A similar representation has been reported in the caudal midbrain and medulla of the frog, as well as in psychophysical movement studies in humans. A head-centered vector representation of this type is generated by two stages of opponent processing that combine corollary discharges of outflow movement signals to the two eyes. This head-centered vector representation interacts with representations of neck movement commands to generate a body-centered estimate of target position. The contributions of the neck command signals to this vector representation are learned during head movements made while the gaze remains fixed on a foveated target. An initial estimate is stored and offset of a gating signal prevents the stored estimate from being reset during a gaze-maintaining head movement. VOR-related circuitry is assumed to control gate offset. As the head moves, new estimates are generated and compared with the stored estimate. If the estimates are unequal, the comparison generates non-zero difference vectors, which act as error signals to drive the learning process.

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A NEURAL NETWORK MODEL FOR CURSIVE SCRIPT PRODUCTION

Daniel Bullock†, Stephen Grossberg‡, and Christian Mannes§

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Boston, MA: Boston University

Biological Cybernetics, in press, 1993

ABSTRACT

This article describes a neural network model, called the VITEWRITE model, for generating handwriting movements. The model consists of a sequential controller, or motor program, that interacts with a trajectory generator to move a hand with redundant degrees of freedom. The neural trajectory generator is the Vector Integration to Endpoint (VITE) model for synchronous variable-speed control of multijoint movements. VITE properties enable a simple control strategy to generate complex handwritten script if the hand model contains redundant degrees of freedom. The proposed controller launches transient directional commands to independent hand synergies at times when the hand begins to move, or when a velocity peak in a given synergy is achieved. The VITE model translates these temporally disjoint synergy commands into smooth curvilinear trajectories among temporally overlapping synergetic movements. The separate "score" of onset times used in most prior models is hereby replaced by a self-scaling activity-released "motor program" that uses few memory resources, enables each synergy to exhibit a unimodal velocity profile during any stroke, generates letters that are invariant under speed and size rescaling, and enables effortless connection of letter shapes into words. Speed and size rescaling are achieved by scalar GO and GRO signals that express computationally simple volitional commands. Psychophysical data concerning hand movements, such as the isochrony principle, asymmetric velocity profiles, and the two-thirds power law relating movement curvature and velocity arise as emergent properties of model interactions.

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A REAL-TIME, UNSUPERVISED NEURAL NETWORK MODEL FOR THE CONTROL OF A MOBILE ROBOT IN A NONSTATIONARY ENVIRONMENT

E. Zalama Casanova, Paolo Gaudiano†, and J. Lopéz Coronado

In preparation, 1993

ABSTRACT

This article introduces a real-time, unsupervised neural network model that learns to control a two-degree-of-freedom (2-DOF) nonholonomic mobile robot in a nonstationary environment. The model combines associative learning and Vector Associative Map (VAM) learning to generate transformations between spatial and velocity coordinates. The transformations are generated in an initial training phase, during which the robot moves as a result of endogenously generated velocities applied to the robot's wheels. The robot learns the relationship between these small velocities and the resulting incremental movements. During performance, the use of a VAM architecture enables the robot to generalize from the learned incremental movements to reach targets at arbitrary distance and angle from the robot. The VAM structure also enables the robot to perform successfully in spite of drastic changes to the robot's plant, including changes in wheel radius, changes in inter-wheel distance, or changes in the internal time step of the system. This article describes the model, presents illustrative simulation results that include both target and trajectory tracking, and compares the model to other neural network and classical approaches to control.

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CEREBELLAR LEARNING IN AN OPPONENT MOTOR CONTROLLER FOR ADAPTIVE LOAD COMPENSATION AND SYNERGY FORMATION

Daniel Bullock†, José L. Contreras-Vidal‡, and Stephen Grossberg§

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Boston, MA: Boston University

In Proceedings of the World Congress on Neural Networks
Hillsd e, NJ: Erlbaum Associates, in press, 1993

ABSTRACT

This paper shows how a minimal neural network model of the cerebellum may be embedded within a sensory-neuro-muscular control system that mimics known anatomy and physiology. With this embedding, cerebellar learning promotes load compensation while also allowing both coactivation and reciprocal inhibition of sets of antagonist muscles. In particular, we show how synaptic long term depression guided by feedback from muscle stretch receptors can lead to trans-cerebellar gain changes that are load-compensating. It is argued that the same processes help to adaptively discover multi-joint synergies. Simulations of rapid single joint rotations under load illustrates design feasibility and stability.

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A SELF-ORGANIZING NEURAL NETWORK FOR LEARNING A BODY-CENTERED INVARIANT REPRESENTATION OF 3-D TARGET POSITION

Daniel Bullock, Douglas Greve, Stephen Grossberg, and Frank H. Guenther

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Boston, MA: Boston University

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ABSTRACT

This paper describes a self-organizing neural network that rapidly learns a body-centered representation of 3-D target positions. This representation remains invariant under head and eye movements, and is a key component of sensory-motor systems for producing motor equivalent reaches to targets (Bullock, Grossberg, and Guenther, 1993).

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AN UNSUPERVISED ERROR-BASED NEURAL NETWORK MODEL FOR THE GENERATION AND CONTROL OF MOVEMENT TRAJECTORIES

Paolo Gaudiano†

Invited Article:
1993 AAAS Science Innovation Conference
August 6-10, 1993, Boston, Massachusetts

ABSTRACT

How can humans and animals be able to carry out novel motor tasks that they have never learned before? How is perceptual information about their environment transformed into spatial representations that can be used to generate accurate motor commands? In this talk I will present the Vector Associative Map (VAM), a self-organizing, unsupervised neural network model that has been applied to a variety of problems in the adaptive control of movemente trajectories. The VAM was derived from the Vector Integration To Endpoint (VITE) model (Bullock & Grossberg, 1988, *Psych. Rev.*, **95**, 49) for the generation and control of movement trajectories. The VAM model has been applied to a variety of learning tasks, including intramodal calibration of arm control parameters, intermodal learning of spatial-to-motor maps (Gaudiano & Grossberg, 1991, *Neural Networks*, **4**, 147), and learning an invariant representation of 3-D target positions in head-centered coordinates (Guenther, Bullock, Greve, Grossberg, *J. Cog. Neurosci.*, in press). The VAM model advances our understanding of brain function in the realm of adaptive motor control, and it holds great potential for practical applications in robotics and control.

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A NONLINEAR MODEL OF SPATIOTEMPORAL RETINAL PROCESSING: SIMULATIONS OF X AND Y RETINAL GANGLION CELL BEHAVIOR

Paolo Gaudiano†

Technical Report CAS/CNS-TR-93-048
Boston, MA: Boston University

Submitted to *Vision Research*, 1993

ABSTRACT

This article introduces a nonlinear model of neural processing in the vertebrate retina, comprising model photoreceptors, model push-pull bipolar cells, and model ganglion cells. Analyses and simulations show that the model can account for several aspects of both X and Y cat retinal ganglion cell behavior. In particular, with a choice of parameters that mimics *beta* cells, the model exhibits X-like linear spatial summation (null response to contrast-reversed gratings) in spite of photoreceptor nonlinearities; on the other hand, a choice of parameters that mimics *alpha* cells leads to Y-like frequency doubling. These and other results suggest that X and Y cells can be seen as variants of a single neural circuit. The model also suggests that both depolarizing and hyperpolarizing bipolar cells converge onto both ON and OFF ganglion cell types, although the effects of this push-pull convergence can be elusive when recording from individual ganglion cells. These hypotheses are supported in the article by a number of computer simulation results.

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BOUNDARY, BRIGHTNESS, AND DEPTH INTERACTIONS DURING PREATTENTIVE REPRESENTATION AND ATTENTIVE RECOGNITION OF FIGURE AND GROUND

Stephen Grossberg†

Technical Report CAS/CNS-TR-93-003
Boston, MA: Boston University

In celebration of the 80th birthday of Professor Gaetano Kanizsa
and the 20th anniversary of the Italian Journal of Psychology

ABSTRACT

This article applies a recent theory of 3-D biological vision, called FACADE Theory, to explain several percepts which Kanizsa pioneered. These include 3-D pop-out of an occluding form in front of an occluded form, leading to completion and recognition of the occluded form; 3-D transparent and opaque percepts of Kanizsa squares, with and without Varin wedges; and interactions between percepts of illusory contours, brightness, and depth in response to 2-D Kanizsa images. These explanations clarify how a partially occluded object representation can be completed for purposes of object recognition, without the completed part of the representation necessarily being seen. The theory traces these percepts to neural mechanisms that compensate for measurement uncertainty and complementarity at individual cortical processing stages by using parallel and hierarchical interactions among several cortical processing stages. These interactions are modelled by a Boundary Contour System (BCS) that generates emergent boundary segmentations and a complementary Feature Contour System (FCS) that fills-in surface representations of brightness, color, and depth. The BCS and FCS interact reciprocally with an Object Recognition System (ORS) that binds BCS boundary and FCS surface representations into attentive object representations. The BCS models the parvocellular LGN→Interblob→Interstripe→V4 cortical processing stream, the FCS models the parvocellular LGN→Blob→Thin Stripe→V4 cortical processing stream, and the ORS models inferotemporal cortex.

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A NEURAL NETWORK MODEL OF DYNAMIC RECEPTIVE FIELD REORGANIZATION

P. Gaudiano, S. Olson, D. Tal, and B. Fischl

Society for Neuroscience Abstracts, Washington, DC, 1993

ABSTRACT

Primary sensory cortex is traditionally viewed as a passive filter, extracting information for processing in higher cortical centers. However, recent experiments have revealed a remarkable degree of plasticity in primary sensory cortex, particularly in visual cortex (Gilbert, 1992; Heinen & Skavenski, 1991; Kaas *et al.*, 1991) and somatosensory cortex (Merzenich *et al.*, 1984; Pons *et al.*, 1991; Ramachandran *et al.*, 1992). Receptive fields of cells in visual cortex have been shown to respond dynamically to changes in the visual environment, both within and outside the cells' classically defined receptive fields. This reorganization occurs on a variety of time scales, from seconds to years (Gilbert, 1992). We show a simple neural network model based on Adaptive Resonance Theory (ART: Carpenter & Grossberg, 1987; Grossberg, 1976) that displays some of the dynamical reorganization found in visual and somatosensory cortex. According to ART, plasticity is maintained throughout life, although feedback interactions prevent spurious reorganization during normal cortical function. In qualitative agreement with experimental results, simulated cortical cell receptive fields expand and contract as a result of attentional influences, real and artificial retinal lesions (both immediate and long-term reorganization), and preferential stimulation. Information from outside a cell's receptive field directly and indirectly mediates the cell's response. Both the rapid and long-term receptive field reorganizations arise as a consequence of nonlinear network-level interactions that are not fully explicable by examining the responses of individual neurons.

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